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Measurement Errors in Tipping Bucket Rain Gauges under Different Rainfall Intensities and their implication to Hydrologic Models

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Abstract. *Measurements from tipping bucket rain gauges (TBRs) consist of systematic and random errors as an effect of external factors, such as mechanical limitations, wind effects, evaporation* *losses, and rainfall intensity. Two different models of TBRs, viz. ISCO-674 and TR-525 (Texas Instr., Inc.), being used in Ohio's Upper Big Walnut Creek Watershed, were calibrated in the lab to quantify measurement errors at different rainfall intensities. A range of rainfall intensities (12.5 to 230 mm-hr^{-1}) was simulated for each TBR using a pre-calibrated peristaltic pump mechanism. The instantaneous and cumulative values of simulated rainfall were measured at 1-min intervals. Actual and measured rainfall at each intensity was compared. Both TBR measurements showed a significant deviation from the actual rainfall rates with increasing underestimation error at higher intensities (>50.8 mm-hr^{-1}) and slight overestimation at lower intensities (<25.4 mm-hr^{-1}). Model TR-525 showed an earlier and larger deviation (up to 20%) as compared to ISCO-674 (up to 13%) over the range of intensities. These findings are being used to correct precipitation data being collected by both TBRs and test the effect of these corrections on the outputs of hydrologic models, such as SWAT and DRAINMOD.*

Keywords. Rainfall, Rain gauge, Tipping bucket rain gauge, TBR, Calibration, Measurement error

Introduction

In the U.S.A., climatic records have been collected and compiled at many stations for more than a century. The network of these meteorological stations consists of about 300 “first order stations” and about 8000 “cooperative stations” spread out throughout the country (Hopkins, 2007). The standard 8” non-recording precipitation gauge (SNRG) has been used as the official precipitation measurement instrument for the U.S. climate station network by the National Weather Service (NWS). About 241 first order stations and around 2600 cooperative stations in the U.S. record hourly totals of precipitation. A majority of them (about 30% of the total of approximately 12,000 gauges) use three main types of automated recording gauges: Tipping Bucket Rain gauges (TBR), Universal Weighing rain gauges, and Fischer and Porter-Belfort rain gauges.

Tipping bucket rain gauges became popular because of their simple, durable and inexpensive design; and most importantly, their applicability to the remote areas. They can be installed in remote areas and can be easily connected to a variety of monitoring and/or recording devices. However, several historical studies revealed that the measurements from TBRs can consist of errors as an effect of several external factors such as wind effects, evaporation losses, rainfall intensity etc. (Parsons, 1941; Sevruk and Hamon, 1979; Groisman, et al., 1999; Molini et al., 2005). These errors can be categorized as Systematic and/or Random, and can be be minimized to some extent by various calibration techniques.

Similar deviations were observed in the precipitation data collected by a TBR as compared to those collected by an adjacent SNRG in the Upper Big Walnut Creek Watershed (UBWC). Therefore, a study was conducted in the lab to calibrate two TBR models and quantify the associated measurement errors. The results of the study are used to correct long-term data collected by the TBRs in this watershed project. This paper also discusses the implications of these results to sensitivity and uncertainty analysis of hydrologic models.

Materials and Methods

A lab experiment was set up to calibrate the tipping bucket rain gauges under study. The experiment was divided into several phases, as follows: 1. Volumetric calibration of rain gauge; 2. Calibration of supply pump, and 3. Dynamic calibration of rain gauge.

Experimental Setup

Figure 1 shows the setup for calibration of rain gauges. A peristaltic pump (Masterflex, Inc.) was used to generate a range of flow rates required to simulate different rainfall intensities. A flow controller was used to vary the speed of rotor, and hence, the flow rate of the pump. The flow from pump was supplied through rubber tubing to the rain gauge under test. TBRs were connected to a CR-10 data-logger, which records number of bucket tips as pulse inputs at an interval of 1 minute. The CR-10 data logger was programmed such that it records each pulse as 0.254 mm of instantaneous rainfall and also calculates and records the cumulative rainfall. A constant inlet head and 12 V DC supply was ensured during the experiment, in order to achieve constant pump discharge and accurate data recording.

A volumetric calibration of both TBR models was conducted before conducting the actual experiment. Each TBR was placed on a level platform. Tipping bucket mechanism in each gauge was tested for volume of water required to tip the bucket. A 10-ml pipette fixed at the same height as the outlet of the funnel was used to supply water. As one bucket tip is associated with 0.254 mm of rainfall, the volume required to tip the bucket may be calculated as:

$$Vtip\ (mL) = 0.0254\ cm \times (\Pi \times D^2)/4$$

Where: D is the collecting diameter of the rain gauge, cm.

The tipping bucket mechanism was calibrated with the help of adjusting screws, such that both the buckets tip at the same volume, equivalent to 0.254 mm of rainfall.

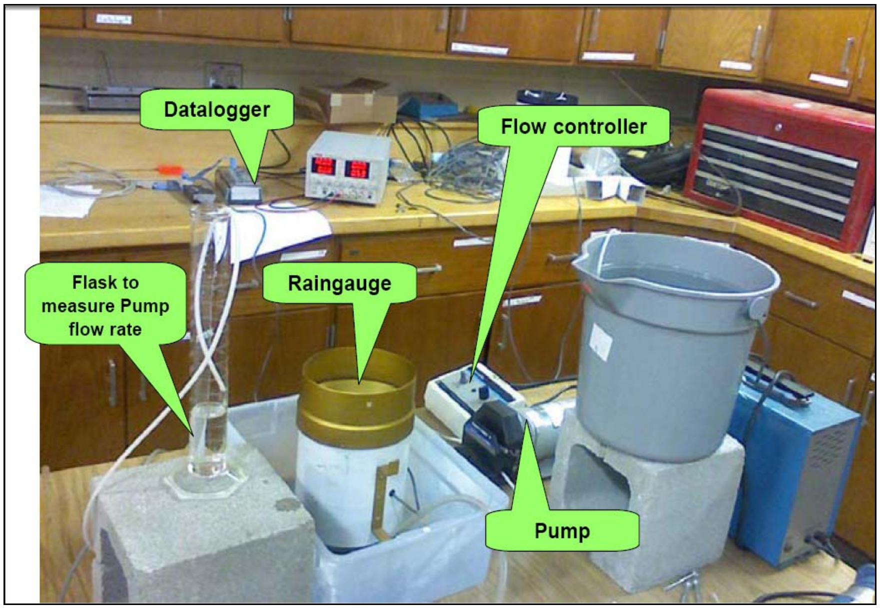

Figure 1. Experimental set up for calibration of TBR model TR-525.

The peristaltic pump was calibrated for consistent discharge over a range of flow rates. The pump discharge at each flow rate was measured in three replications at an interval of 30 sec. with the help of a measuring cylinder and stop watch (Figure 1).

Dynamic calibration of the TBRs was conducted by testing each for flow rates simulated by the peristaltic pump mechanism. At each rainfall rate, after the TBR reached steady operating condition, data were recorded at 1-min intervals for at least 15 minutes. A range of flow rates (i.e., rainfall intensities), starting from 12.5 mm-hr^{-1} to 230 mm-hr^{-1} was applied and the same procedure was repeated for each flow rate. Rainfall rates measured by the TBRs were compared with the respective (actual) rates simulated by the pump mechanism.

Corrections to Collected Data

Based on experimental data, it is proposed to correct the data collected by TBR models installed in the UBWC watershed. A correction protocol is under development that will be used to correct the field data. The TBRs in UBWC watershed record rainfall data at 10-min intervals. The long-term data will be divided into individual events of different intensities and corrections will be applied based on intensities and other relevant factors.

Model Sensitivity

The corrected data will be used to simulate hydrology of the watershed and/or its sub-watersheds using hydrologic models such as DRAINMOD and SWAT. Sensitivity of these models to the corrections in rainfall data will be tested by comparing the models results with those for original rainfall data. This work is under progress and its results will be included in the final presentation of this paper.

Results and Discussion

Volumetric calibration of TBRs proved to be an important step before conducting the experiment. The average volume of water required for one bucket tip was found to be 4.64 ml for model TR-525 and 8.24 ml for the ISCO-674. The calibration screws at the bottom of the tipping bucket mechanism were adjusted for the desired volumes, such that one tip represents 0.254 mm (0.01 in) of rainfall. Figure 2 shows the calibration curve for peristaltic pump mechanism. At any specified rate, the pump mechanism supplied fairly constant discharge. Statistical analysis shows no significant variation of discharge at any flow rate.

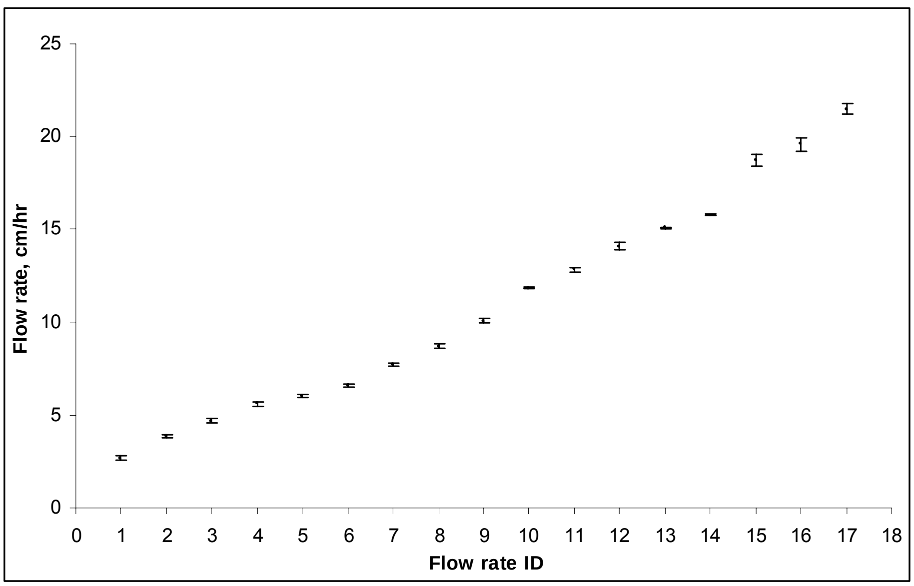

Figure 2. Calibration curve for peristaltic pump (dots indicate average flow rate and bars indicate standard deviation of flow rate).

Dynamic calibration showed that both TBR models under-estimate rainfall at higher intensities. The results for dynamic calibration of TBRs have been summarized in Figure 3 and Table 1.

The instantaneous and cumulative values of simulated rainfall were measured at 1-min intervals. Both TBR measurements showed a significant deviation from the actual rainfall rates with increasing under-estimation error at higher intensities. Model TR-525 showed an earlier deviation in measurements starting at an intensity of 4 cm-hr^{-1}. On the other hand, model ISCO-625 showed a delayed response with measurement errors starting at an intensity of 5.5 cm-hr^{-1}. Under-estimation errors were larger (up to 20%) for the TR-525 as compared to those of the ISCO-674 (up to 13%) over the range of intensities. The tendency of TBRs to under-estimate rainfall at higher intensities may be attributed to the loss of water during the tipping movement of the two buckets. There is some time lapse between the start of movement of first bucket and the instance when second bucket comes under the funnel. During this time, some water is lost as it falls into the first bucket during its tipping movement. If we assume that the tipping time of buckets remains constant, then larger amounts of water will be lost at higher flow rates, and hence result in greater under-estimation errors. On the other hand, bucket volume is an important factor affecting under-estimation errors. If the water loss during tipping movement (i.e., during lapse time) is a small fraction of bucket volume, then the error will be small. Model TR-525 has a bucket volume of 4.64 ml; while ISCO-674 has a bucket volume of 8.24 ml. At any given rainfall intensity, the former will record a greater number of tips as compared to the later.

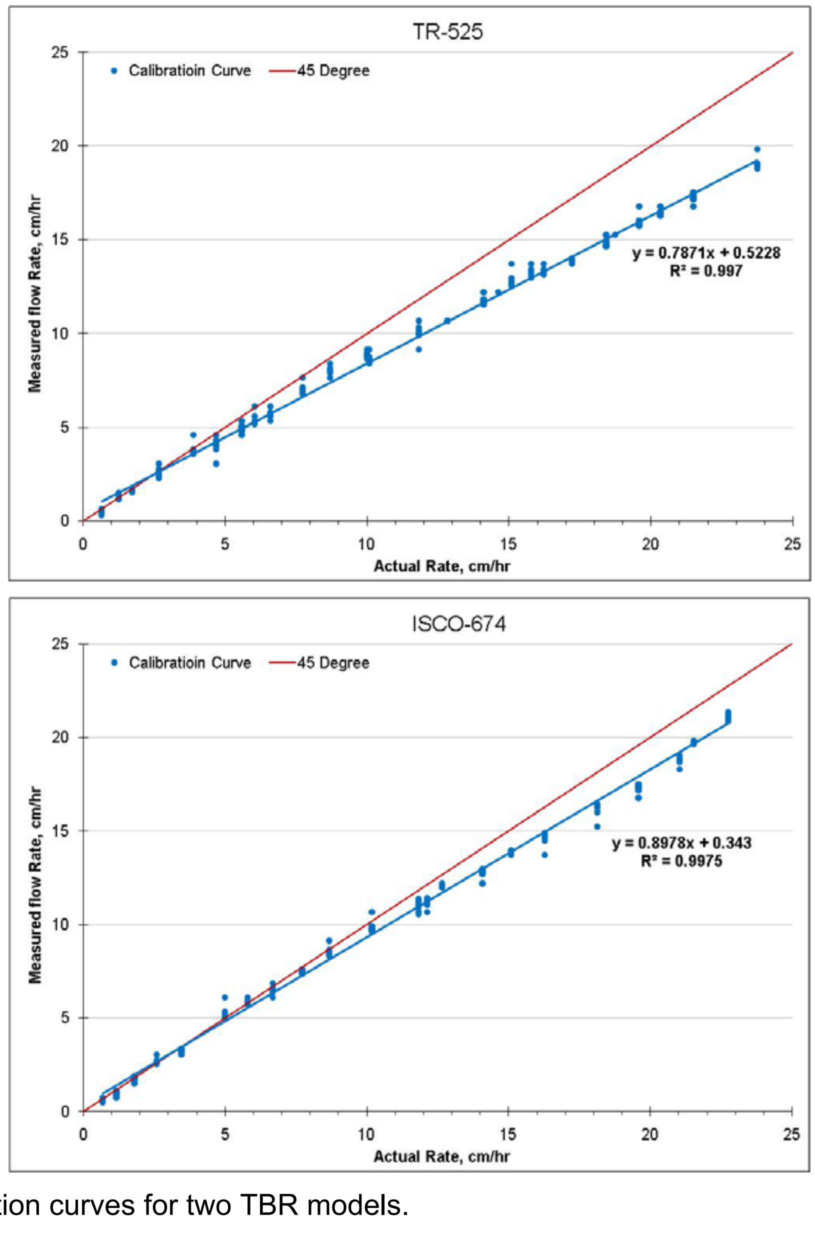

Figure 3 Calibration curves for two TBR models.

Both TBR models showed slight over-estimation at lower rainfall intensities (< 2.54 cm-hr^{-1}). With the existing experimental set up, it was difficult to maintain accuracy in measurements and time at very low flow rates.

Table 1. Errors in TBR measurements of rainfall intensities as compared to actual flow rates.

TR-525			**ISCO-674**		
Actual (cm-hr^{-1})	Measured (cm-hr^{-1})	Error %	Actual (cm-hr^{-1})	Measured (cm-hr^{-1})	Error %
0.66	0.55	16.8	0.70	0.69	1.5
1.26	1.25	0.6	1.18	1.03	13.1
1.73	1.61	6.6	1.81	1.77	2.3
2.68	2.58	3.8	2.60	2.63	-1.3
3.88	3.72	4.3	3.47	3.27	5.7
4.69	4.12	12.3	5.01	5.14	-2.8
5.59	4.89	12.6	5.80	5.89	-1.6
6.05	5.33	11.9	6.68	6.49	2.9
6.60	5.71	13.4	7.72	7.48	3.1
7.73	6.90	10.8	8.68	8.45	2.6
8.69	8.00	8.0	10.19	9.82	3.6
10.00	8.85	11.6	11.82	11.21	5.2
10.08	8.71	13.6	12.12	11.29	6.8
11.83	10.03	15.2	12.66	12.07	4.6
12.84	10.67	16.9	14.08	12.89	8.5
14.10	11.65	17.4	15.09	13.86	8.1
14.63	12.19	16.7	16.28	14.78	9.2
15.08	12.66	16.1	18.12	16.33	9.9
15.79	13.31	15.7	19.58	17.36	11.4
16.22	13.23	18.4	21.02	18.80	10.6
17.23	13.82	19.8	21.52	19.72	8.3
18.42	14.75	19.9	22.73	21.12	7.1
18.74	15.24	18.7			
19.59	15.82	19.2			
20.33	16.38	19.4			
21.49	17.20	20.0			
23.74	18.98	20.0			

Corrections to field data

Based on the experimental data, simple linear regression equations were developed to correct the long term rainfall data collected by the TBR models. The following equations were proposed for corrections in rainfall intensities:

For TR-525: $I_a = 1.2667 I_m - 0.6277$

For ISCO-674: $I_a = 1.111\, I_m - 0.3546$

Where: Ia is actual rainfall intensity (cm-hr^{-1}); and Im is rainfall intensity measured by the TBR (cm-hr^{-1}).

However, after reviewing the observed field collected data, it was found that the finest time resolution of the data collected by any of the TBRs is 10 min. Therefore, the following regression models were developed for correcting 10-min rainfall totals collected by the two TBRs (Figure 4).

For TR-525: Y = 1.2692X – 1.1089

For ISCO-674: Y = 1.1143X – 0.6538

Where: Y is the actual value of 10-min rainfall (cm); and X is the value of 10-min rainfall measured and recorded by the TBR (cm).

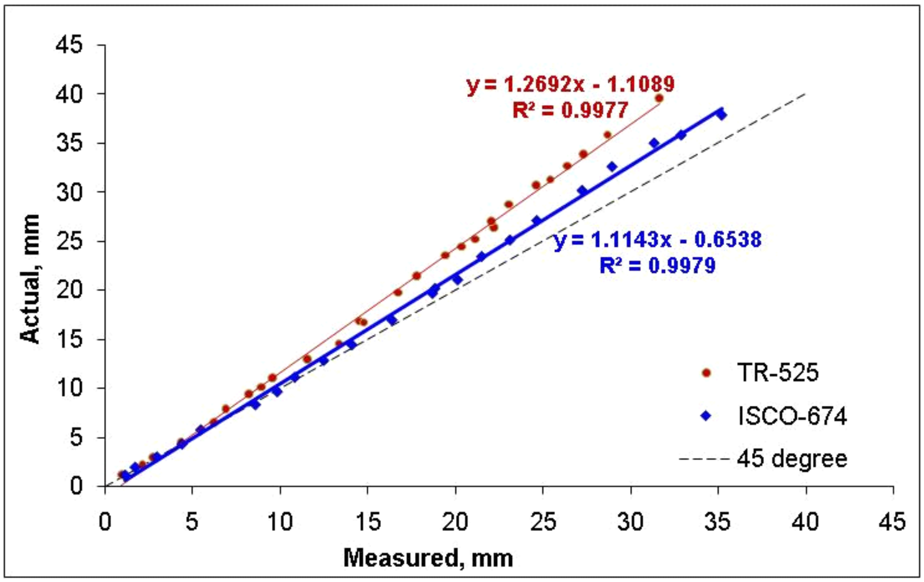

Figure 4. Calibration curve for TBRs based on 10-min totals of rainfall.

Because of the coarse time resolution (10 min), the actual maximum rainfall intensities could not be represented. Several studies have reported that the tipping time does not remain constant, and changes with intensity. A methodology is being developed to take into account all these factors before applying the corrections to the long-term rainfall data. Work is under way to determine the average tipping time by experimental method. The rainfall data will be classified based on maximum rainfall intensities and corrections will be applied to the data.

Model Sensitivity to the corrections

The corrected as well as uncorrected long-term rainfall data will be used in hydrologic modes, such as DRAINMOD to simulate hydrology in the UBWC watershed. Sensitivity of the models to these corrections will be tested by comparing the model results for corrected and uncorrected data. This work is in progress and will be presented during the actual presentation of this paper.

Summary and Conclusions

In this study, a lab experiment was conducted to dynamically calibrate two TBRs for estimating the associated measurement errors. The results indicate that both the TBR models showed significant under-estimation errors in measurements at high rainfall intensities. The Model TR-

525 was found to be more sensitive to rainfall intensities with earlier and larger deviations from actual values, as compared to the Model ISCO-674. Both TBR models showed slight over-estimation in measurements at lower rainfall intensities. The deviations in TBR measurements may be attributed to the small amount of water loss during each tipping movement. Bucket volume and tipping time of buckets were discussed to be important factors affecting the measurement errors in TBR models.

Based on the experimental data, simple linear regression models were developed and proposed in this paper to correct measured rainfall intensities and 10-min rainfall totals being recorded in the UBWC watershed. A methodology is being developed to correct the long-term rainfall data measured in the UBWC watershed using the two TBR models under study.

Results of this study will be used to test the sensitivity of hydrologic models such as DRAINMOD in predicting hydrology in UBWC watershed. The simulation results for corrected and uncorrected data will be compared and a final protocol will be developed to apply the corrections to the rainfall data in UBWC watershed.

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